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Procedures for Evaluating the Photopic Response of the Visible Emission Training School Transmissometer

PEDCo-Environmental, Inc., Cincinnati, OH

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PROCEDURES FOR EVALUATING THE PHOTOPIC RESPONSE OF THE VISIBLE EMISSION TRAINING SCHOOL TRANSMISSOMETER

by

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ABSTRACT

PROCEDURES FOR EVALUATING PHOTOPIC RESPONSE OF THE VISIBLE EMISSION TRAINING SCHOOL TRANSMISSOMETER

The basic concept of photopic response is a major factor in the design of the smoke generator transmissometer used at visible emission training schools. The term "photopic" refers to having the daylight spectral response characteristics of the human eye. This study evaluated three transmissometer systems, the reference daylight-photopic system, the tungsten-photopic system, and the tungsten-near-photopic system, to determine whether these three systems had significantly different response characteristics. In addition, a simple procedure was developed for checking the photopic response of transmissometer systems. The responses of the tungsten-photopic and tungsten-near-photopic systems are not significantly different from each other for white or black smoke although the response of the daylight-photopic system is different than the responses of both these systems for white and black smoke. Both laboratory and field evaluations were conducted as part of this study and indicated that a simple technique using two peak response filters is adequate for determining peak response of a system. This two-filter technique is a more desirable technique than the use of multiple cutoff filters for auditing photopic response due to field simplicity.

FOREWORD

Measurement and monitoring research efforts are designed to anticipate potential environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Environmental Monitoring Systems Laboratory, Research Triangle Park, North Carolina, has responsibility for: assessment of environmental monitoring technology and systems; implementation of Agency-wide quality assurance programs for air pollution measurement systems; and supplying technical support to other groups in the Agency including the Office of Air, Noise, and Radiation, the Office of Toxic Substances, and the Office of Enforcement.

This study evaluated three basic types of transmissometer systems to determine whether they had significantly different response characteristics. In addition, a simple procedure was developed for checking the photopic response of transmissometer systems.

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SECTION 1

INTRODUCTION

U.S. Environmental Protection Agency (EPA) Reference Method 9, "Visible Determination of the Opacity of Emissions from Stationary Sources," requires smoke generators used for observer certification to be equipped with "photopic" transmissometer systems. "Photopic" is defined as having the daylight spectral response characteristics of the human eye.

The purpose of this study was twofold. First, the study was designed to evaluate the response differences among three basic types of transmissometer systems, one reference "daylight-photopic" system and two other systems commonly used in smoke generator transmissometers. The second objective of this study was to develop a simple procedure for checking the photopic response of transmissometer systems.

SECTION 2

SUMMARY AND CONCLUSIONS

The three transmissometer systems studied in this program included the reference daylight-photopic system, the tungsten-photopic system, and the tungsten-near-photopic system. The purpose of this study was to evaluate whether these three systems had significantly different response characteristics; this evaluation would permit a determination regarding the significance of the photopic specification of Reference Method 9.

Both a laboratory and field evaluation were conducted. The results of these evaluations indicate the following:

1. A simple technique using two peak response filters which permit transmission of light only in a small (narrow) wavelength range, is adequate to determine photopic response of a system.

2. By using the peak-response filter technique, response differences were noted among all three of the systems evaluated. These results are summarized in Table 2.

3. The two-filter technique is more desirable than the use of multiple cutoff filters for auditing photopic response due to field simplicity. A cutoff filter is a filter that permits transmission of light only above or below a particular wavelength thereby effectively "cutting off" the transmission of light at the particular wavelength.

4. The response of the daylight-photopic system to white and black smoke is different than the responses of the tungsten-photopic and tungsten-near-photopic systems. The difference is most pronounced for white smoke and in all cases is less than 5 percent opacity. Tables 3 and 4 summarize these results, which are graphically presented in Figures 14 and 15.

5. The responses of the tungsten-photopic and tungsten-near-photopic systems are not significantly different from each other for black or white smoke.

6. For the light sources evaluated (2700 K to 5900 K), the effect of different tungsten light sources used with a photopic detector is negligible.

At this point, it should be noted that the only near-photopic system tested was a system using an uncorrected selenium photocell (unfiltered to provide visual response). This photocell system was commonly used in generator transmissometer systems prior to the November 1974 revisions to Reference Method 9. Results with other systems (e.g., uncorrected silicon photocell) should be significantly different.

SECTION 3

BACKGROUND

A technically and legally sound visible emission control program is based on the requirements and criteria of EPA Reference Method 9--"Visible Determination of the Opacity of Emissions from Stationary Sources" (40 CFR 60, Appendix A). The specifications for the smoke generator used in the training and certification of opacity readers are summarized in Reference Method 9 as Table 9-1, "Smoke Meter Design and Performance Specifications." An essential part of the specification is verifying the photopic response of the transmissometer system. Figure 1 is a graphic display of a photopic response curve. The wavelength of visible light ranges from approximately 400 to 700 nm with the peak response at about 550 nm.

Since the observer is certified against the opacity values measured by the tranmissometer, it is essential that the transmissometer system has the same response to the light spectrum visible to the human eye. A transmissometer system that is mostly sensitive to ultraviolet or infrared light would be unacceptable because the transmissometer and the human eye would be measuring at different wavelengths.

Because many opacity training smoke generators did not employ transmissometer systems having photopic response, the 1974 revisions to Reference Method 9 added the requirement for a photopic system. According to the current specification, the operator is required to verify from manufacturer's data that the system's photocell does, in fact, have a photopic response. This specification potentially poses two problems. First, without a specific written procedure, quality assurance checks may not be made to determine if the system is photopic. Second, simply specifying that a photocell has a photopic response does not totally define a photopic system, because the system is actually composed of both the photocell and the light source. Method 9 stipulates an incandescent source but a truly photopic system would technically use a "daylight" source. Most commonly used incandescent sources are tungsten filaments

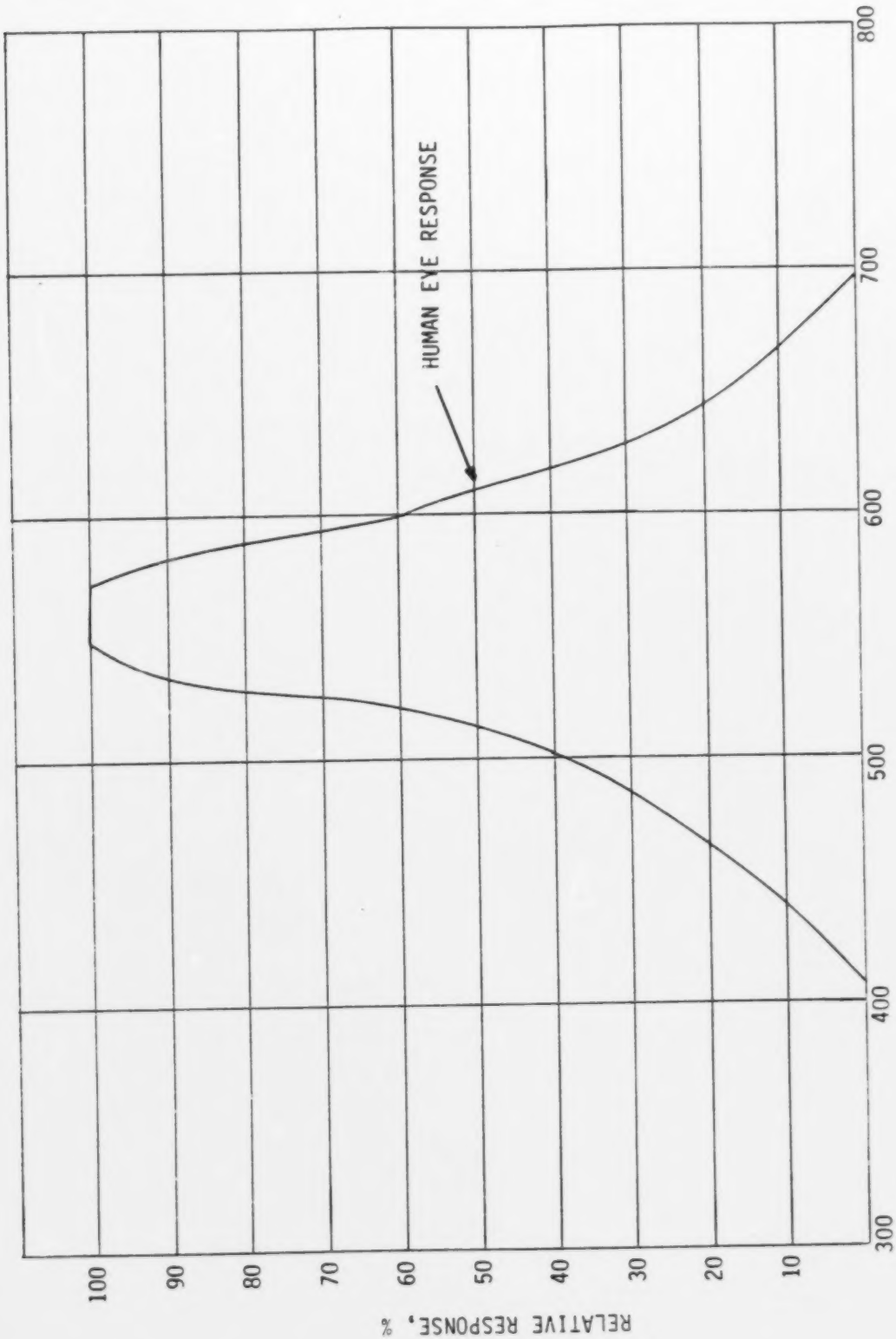


Figure 1. Photopic response curve.[1]

with a color temperature of 2700 to 2900 K, whereas a daylight source would have a color temperature of 5500 to 6000 K. The specification may be inadequate, if a significant response difference exists between a photopic cell-daylight source system and a photopic cell-tungsten source system. The objectives of this study were 1) to investigate the importance of the current photopic specification by evaluating the response differences among three system types, and 2) to develop a simple procedure to check for photopic response of transmissometer systems and to assure that it adequately meets the photopic response criterion established in the Federal Register.

A study[2] was conducted in 1978 by the Quality Assurance Branch of the EPA, Environmental Monitoring Systems Laboratory (EMSL) to determine whether transmissometers on training generators currently in use were meeting the design and calibration requirements of Reference Method 9. This study found that the photopic-response criterion was not being met uniformly, and revealed that no adequate tools existed for assessing the response characteristics (photopic versus near-photopic) or determining how those characteristics might bias the overall results of the smoke plume measurements. The approach taken during the EMSL study was to assess the photopic-response characteristics of the photocell using a series of "cutoff" filters (filters designed to sharply cutoff transmission of light above or below a particular wavelength). This technique compared the amount of light transmitted at a given wavelength to the transmission expected from a photopic system. Figure 2 presents the response curve of a filter used during the EMSL study. This filter, designated No. 4, has a sharp "cutoff" at about 480 nm (i.e., transmits no light at a wavelength below 480 nm, but transmits greater than 90 percent of the light above a wavelength of 480 nm). By using the photopic-response curve (Figure 1) and the response curve of Filter No. 4 (Figure 2), the expected response (transmission or opacity) of a photopic system can be calculated; the calculation yields a photopic-response value of 5 percent opacity for Filter No. 4. The approach of using cutoff filters was chosen by EMSL over the approach of checking the manufacturer's specifications for the photocell for several reasons:[2]

- Some of the photocells were old, and the spectral response may have changed with time.

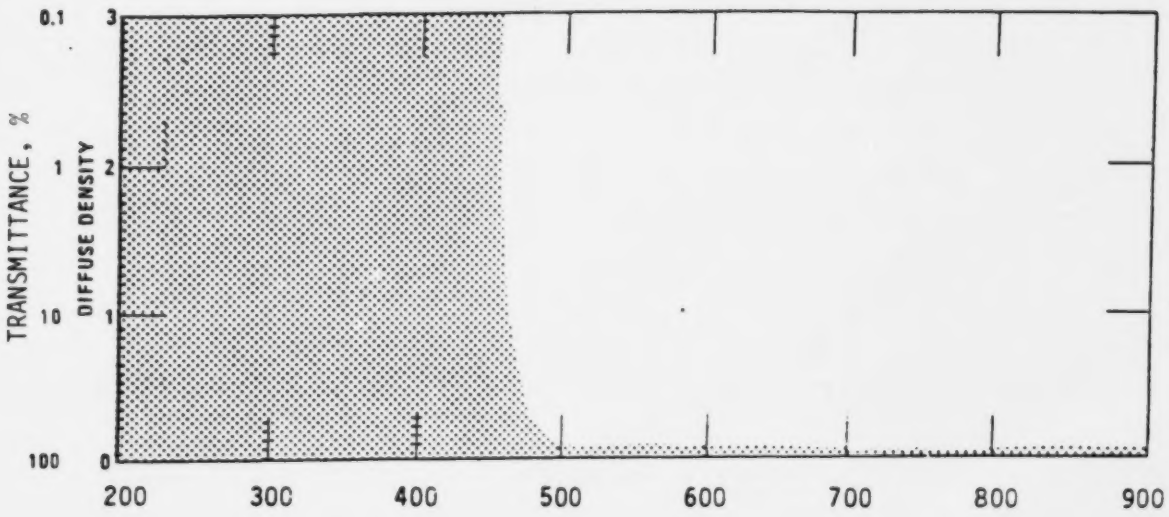


Figure 2. Response curve for Filter No. 4.

- Some of the transmissometers had undergone major modifications, therefore, the photocell might have differed from the one listed in the manufacturer's specifications.

- The manufacturer's spectral response curve data may have been inadequately documented.

- Instrument specifications identifying the photocell may not have been available.

The results of the EMSL study are largely responsible for initiating the work conducted in this study. The EMSL results uncovered a wide range of response among the transmissometers. Perhaps more importantly, the EMSL study demonstrated a need for a standardized definition of "acceptable photopic response," as well as a standardized procedure for determining that response. Reference Method 9 simply requires that the "spectral sensitivity of the cell closely approximate the standard luminosity curve for photopic vision." With the EMSL results, the classification of a photocell as photopic is difficult because there is no definition for "close approximation." The EMSL study clearly indicates a wide range of responses for the different transmissometers to the different cutoff filters. Figure 3 summarizes the results of the study.

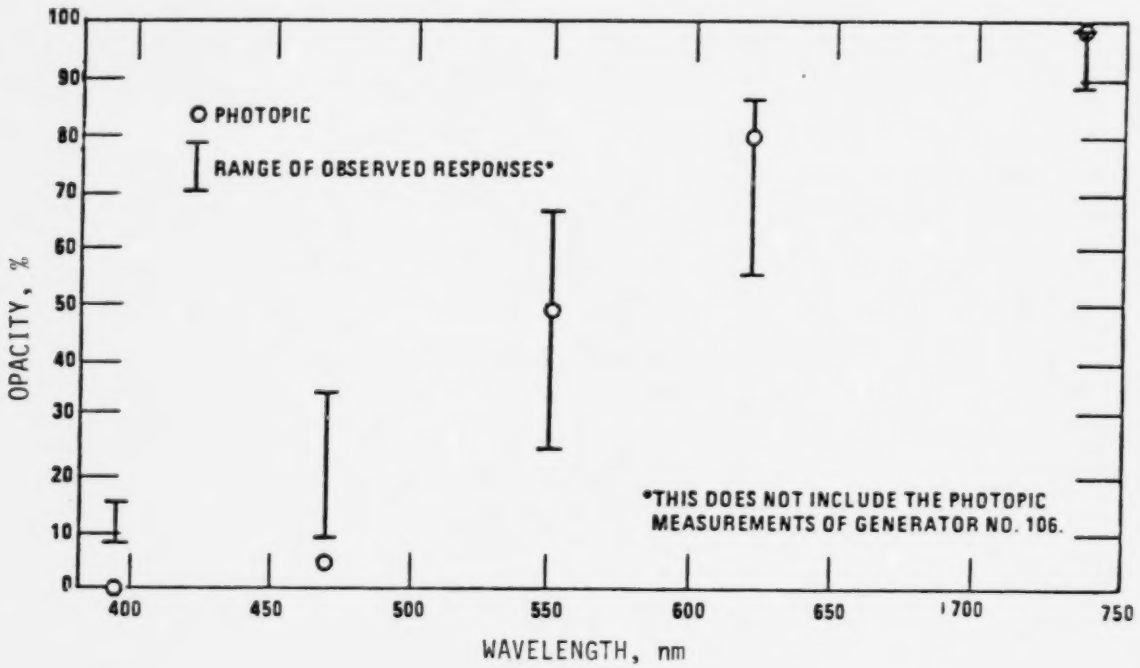


Figure 3. EMSL study results.

SECTION 4

EXPERIMENTAL DESIGN

4.1 EQUIPMENT DESIGN

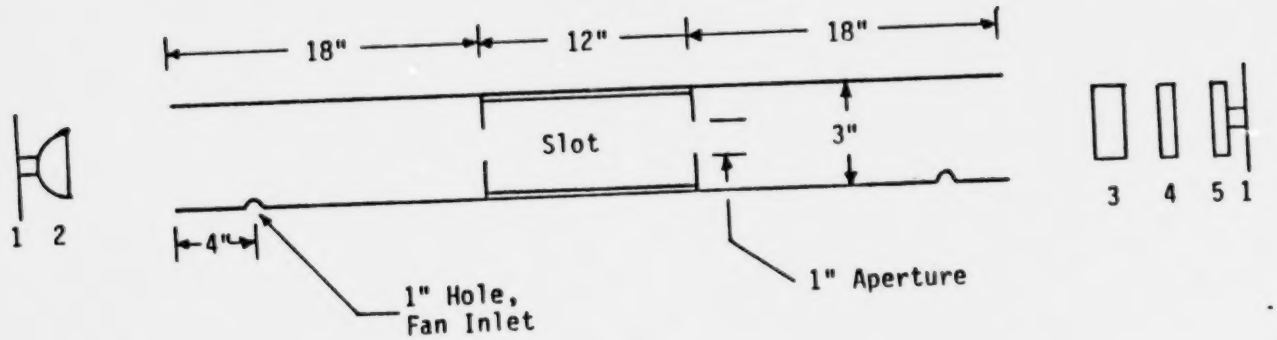
A bench model transmissometer was designed and built to study the response characteristics of the three types of systems to be evaluated. All laboratory experiments were conducted using this transmissometer. The light source, photocells, and filters were varied to obtain the various transmissometer systems included in the study. The three systems evaluated were:

1. Fully Photopic--photopic-response photocell with daylight illumination (color temperature 5500 to 6000 K). This system is totally photopic and is considered the reference standard.

2. Partial Photopic--photopic-response photocell with normal incandescent light source (tungsten filament, color temperature 2700 to 2900 K). This system is used most commonly in field generators and technically meets the specifications of Reference Method 9 because the photocell has a photopic response and the light source is incandescent.

3. Near-Photopic--near-photopic photocell with normal incandescent source (tungsten filament, color temperature 2700 to 2900 K). This system was frequently used in field generators before the November 12, 1974 revisions to Reference Method 9. This system does not meet the present specifications of Reference Method 9 for photopic response because the photocell is known to be near-photopic.

As previously stated, the reference system is the daylight source photopic system that was designed based on National Bureau of Standards (NBS) criteria. Figure 4 illustrates a schematic of this system. Figures 5 and 6 illustrate schematics of the light source and photocell details, respectively.



1 End Plate
2 Light Source
3 Daylight Filter
4 Photopic Filter
5 Photocell Detector

Figure 4. Laboratory transmissometer (exploded view not to scale).

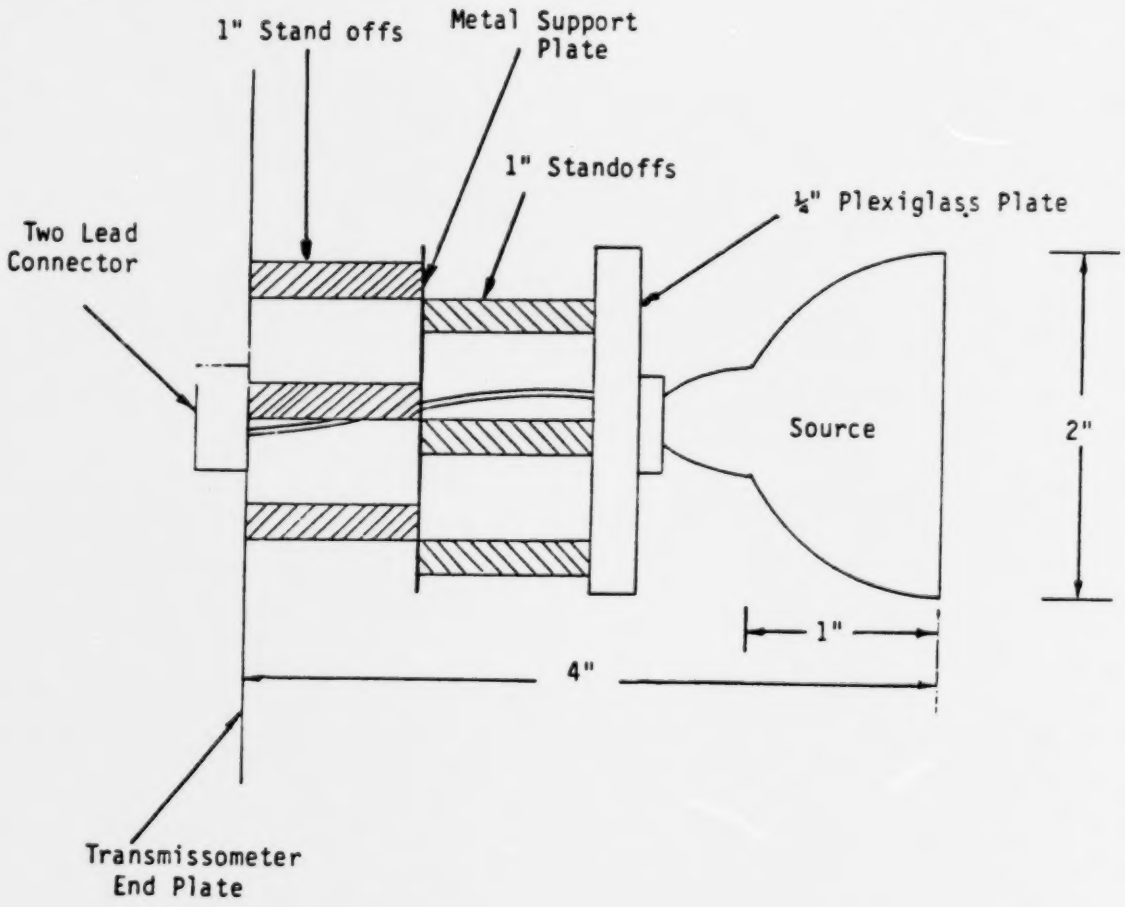


Figure 5. Light source detail GE EPT 2900.

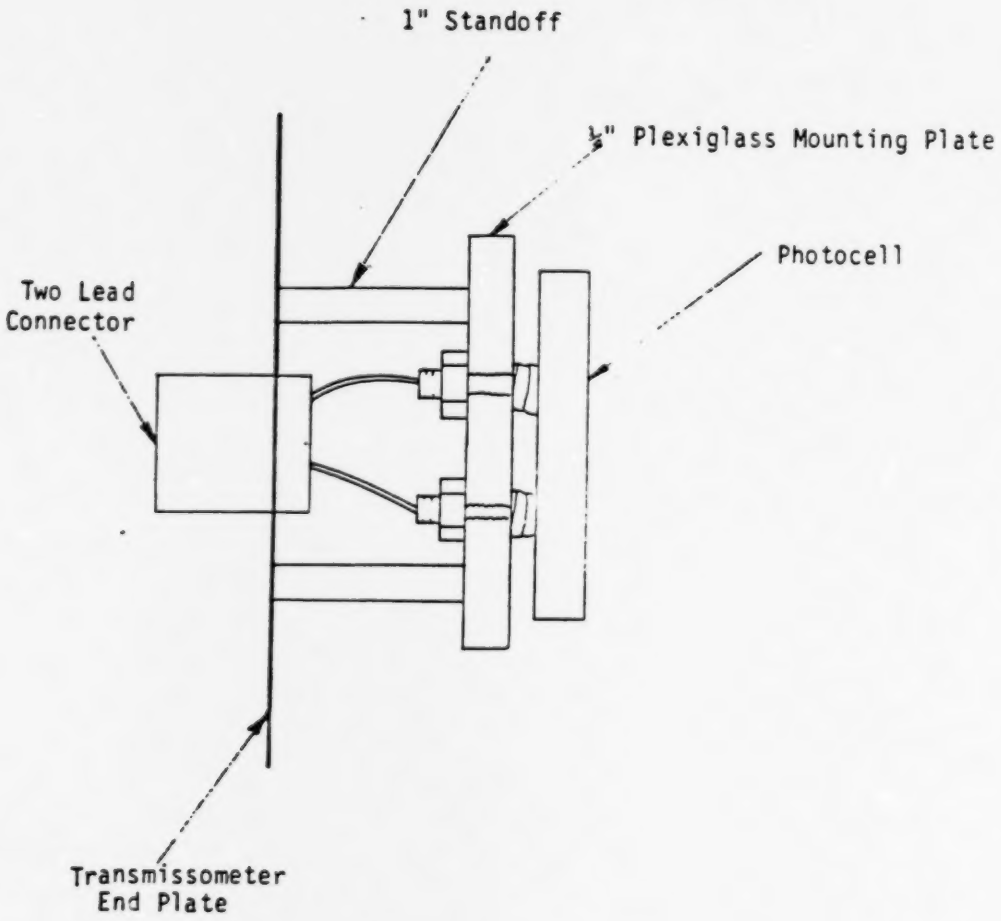


Figure 6. Photocell detail.

The major components of the three systems studied were as follows:

1. Fully Photopic--Daylight Source with Photopic Photocell (Reference)
   Light source: GE EPT 2900 Lamp 10.8 volts, 42 watts (color temperature 3100 K)

   Source filter: Corning Glass Works 5900 Daylight glass filter

   Photocell: Valtec Selenium Model # R75EB

   Photopic filter: Kodak Wratten 102

2. Partial Photopic--Photopic Cell and Incandescent Light Source

   Light source: tungsten source, (color temperature 2700 K). Three different sources were tested:

   No. 1141, 12.8 volt, 1.44 amp
   No. 93, 12.8 volt, 1.04 amp
   No. 1073, 12.8 volt, 1.80 amp

   Source filter: none

   Photocell: Valtec Selenium Model # R75EB

   Photopic filter: Kodak Wratten 102

3. Near-Photopic--Near-Photopic Cell with Incandescent Light Source

   Light source: tungsten source (color temperature 2700 K) Type No. 1141, 12.8 volt, 1.44 amp.

   Source filter: none

   Photocell: Valtec Selenium Model # R75EB

   Photopic filter: none

Figure 7 presents the output characteristics of a normal tungsten source. Figure 8 presents the response characteristics of a selenium photocell, as well as a silicon photocell. Figure 9 presents the transmission characteristics of the Kodak 102 photopic filter. Figure 10 compares the combined response characteristics of a selenium cell corrected with a Kodak 102 filter to the daylight-photopic characteristics of a human eye.

4.2 LABORATORY EVALUATION

The first phase of this study consisted of a laboratory evaluation to determine whether different response characteristics were detectable between

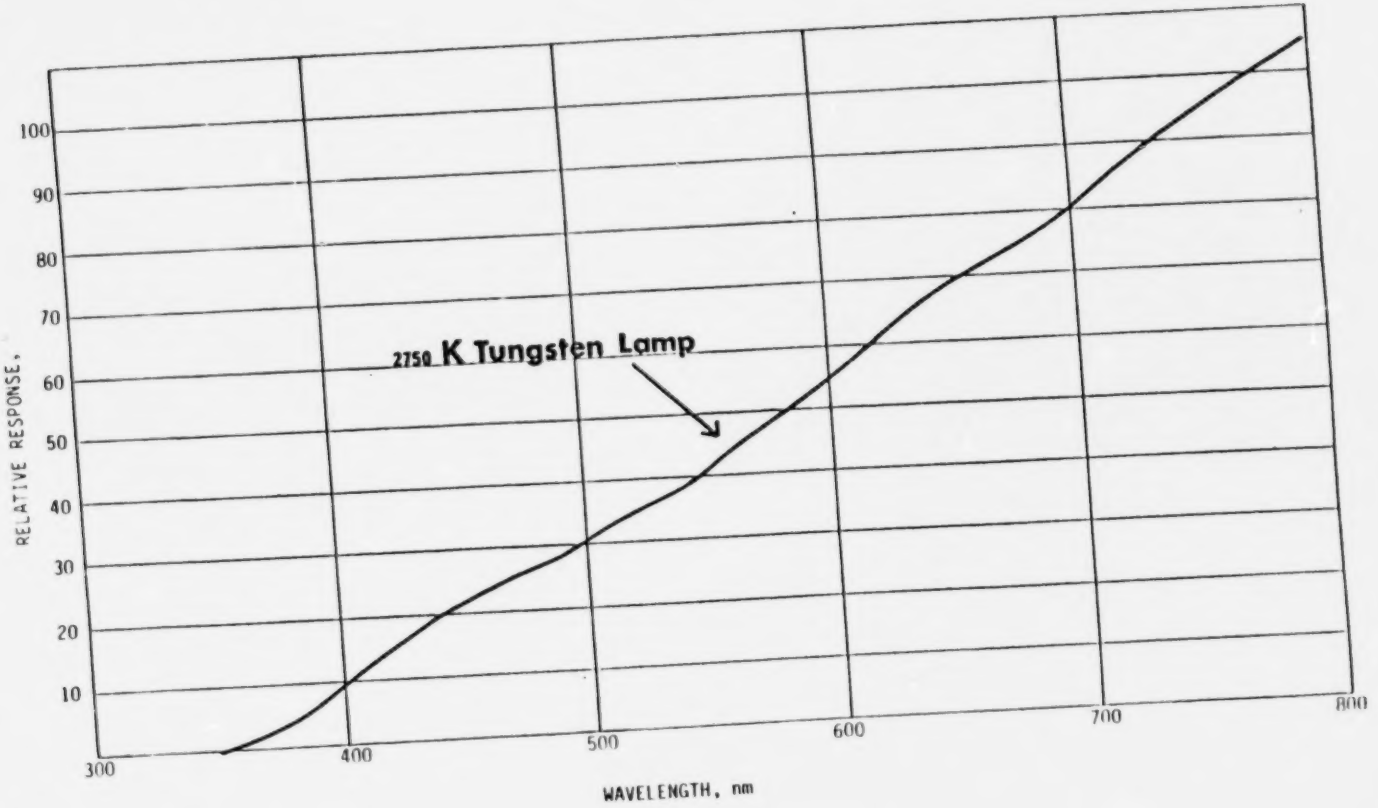


Figure 7. Tungsten source output.

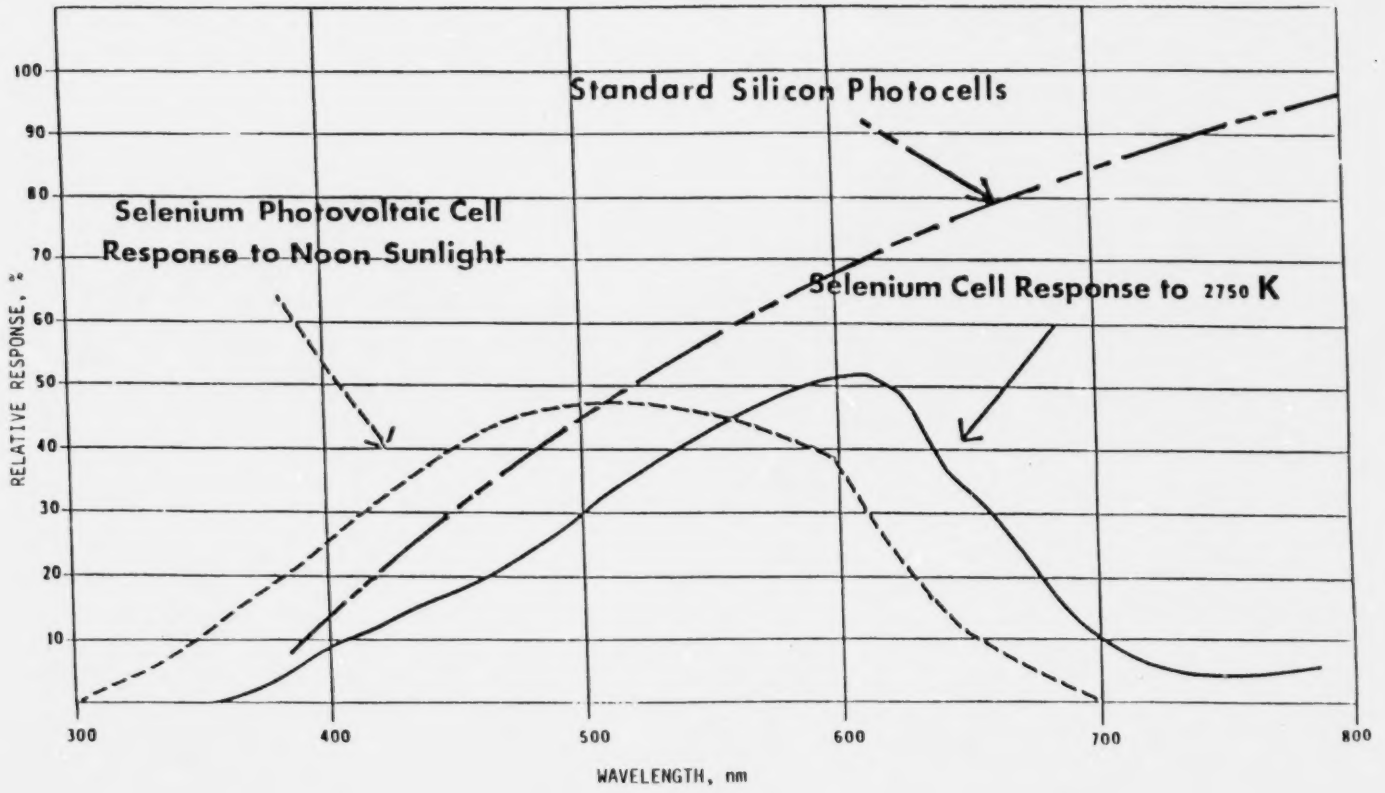


Figure 8. Typical photocell response characteristics.

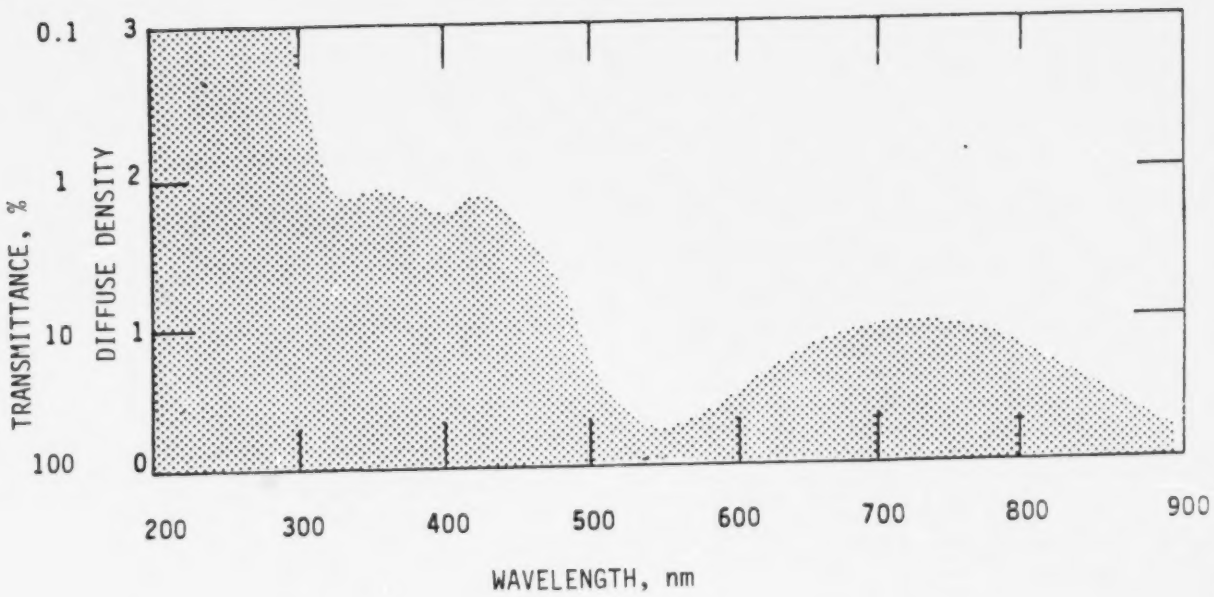


Figure 9. Transmission curve for Filter No. 102 (photopic correction filter for selenium photocell).

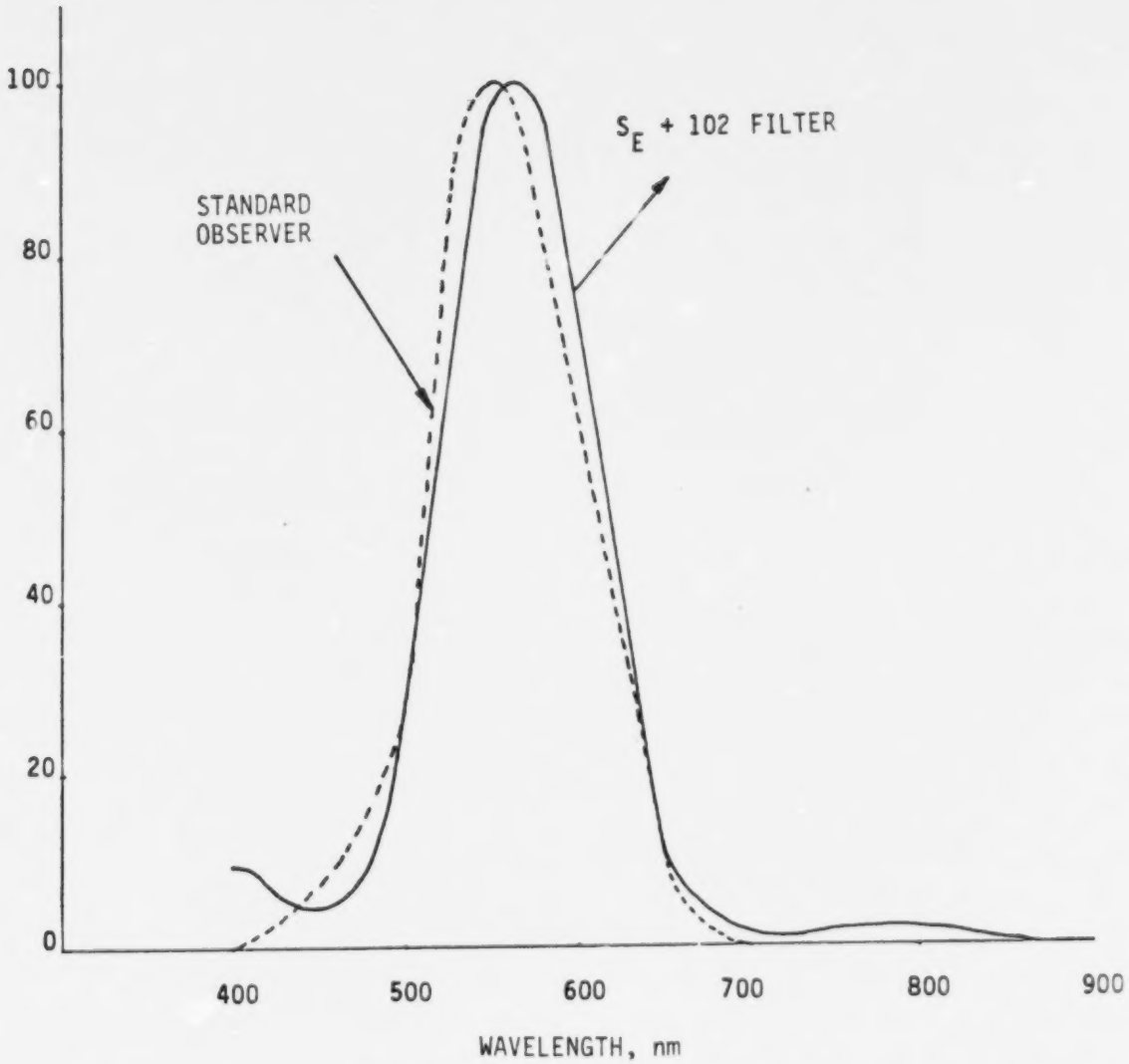


Figure 10. Selenium cell with a Wratten 102 compared to standard observer.

the reference system (fully photopic) and the other systems. A primary objective of this evaluation was to determine if a simple technique could be developed and used as a field audit procedure to determine if a transmissometer system is photopic. A peak-response filter was used to determine whether response differences were detectable. Two peak-response filters were chosen for this experiment, the Kodak No. 58 and the ETA Cellulose Acetate No. 878. Transmission curves for these two filters are presented in Figures 11 and 12, respectively. The transmission curves indicate that these filters transmit light primarily in the 500 to 600 nm range with peak transmittance near 550 nm, the wavelength that the photopic system is most sensitive. Note that the Kodak No. 58 filter has a much narrower transmission band than the ETA No. 878. Kodak Filter No. 58 would be expected to reduce the transmittance from 100 percent to 27 percent for a perfectly photopic system. The ETA No. 878 filter would be expected to reduce transmittance to 45 percent. A near-photopic system emits a greater percentage of the total light energy outside the 400 to 700 nm range. This results in less of the total energy near the peak response area of 550 nm. Consequently, when either the No. 58 or No. 878 filter is inserted into a near-photopic system, a greater reduction in transmittance would be expected because a greater percentage of the total light energy of the system is outside the narrow transmission band of the filter and is consequently filtered out.

The test procedure consisted of first setting up one of the transmissometer systems and conducting a zero/span test. NBS traceable filters (transmittance of 80, 49, and 25%) were used to check the transmissometer linearity. Once linearity was established, the peak-response filters were inserted and the percent transmittance noted. The zero and span were rechecked after the runs were completed. The transmissometer was then modified to the next system type and the procedure repeated.

This procedure was later repeated using the series of cutoff filters used during the EMSL study, in lieu of the peak-response filters.

4.3 FIELD STUDY

The next phase of the study consisted of testing the three basic transmissometers on an operating smoke generator. A smoke generator was set up to

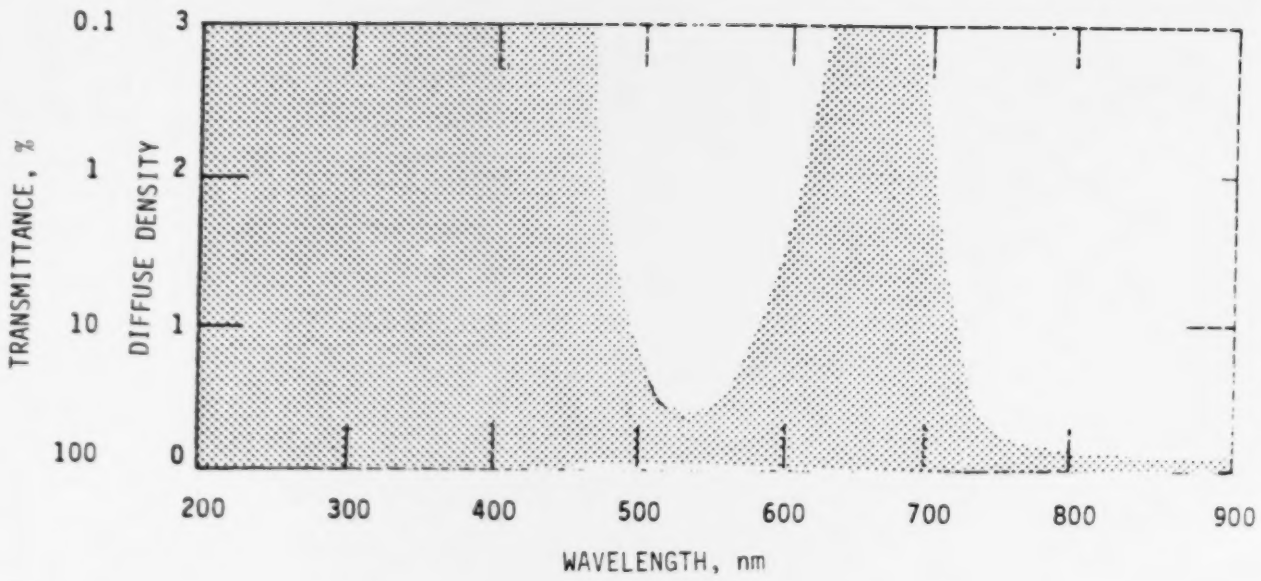


Figure 11. Transmission curve for peak response Filter No. 58.

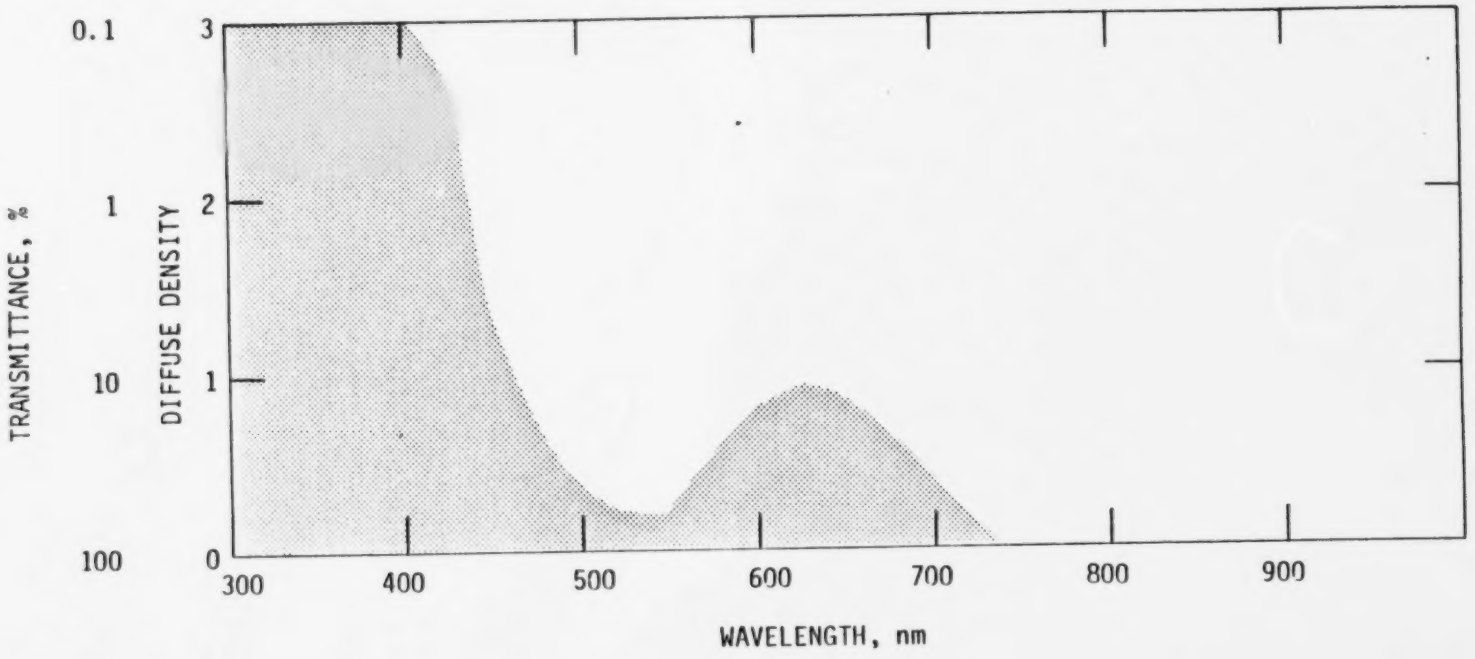


Figure 12. Transmission curve for peak response Filter No. ETA 878.

allow two transmissometers to simultaneously monitor the stack emissions. One transmissometer was set up with the reference system; this unit was identified as transmissometer 2. The other transmissometer system was set up as a partial photopic system and identified as transmissometer 1. A series of tests were conducted using both black and white smoke, and the readings from both transmissometers were recorded.

The tests were repeated using the near-photopic system identified as transmissometer 3 and the same reference transmissometer (transmissometer 2), simultaneously.

Prior to conducting the smoke generator testing, several quality assurance (QA) checks were made to check for bias. The first check determined whether the transmissometer readings were affected by position in the stack. A smoke plume was tested with identical transmissometers in the two different test positions. The transmissometer location was determined to be unimportant. This was further tested by exchanging the control and test transmissometer positions. Again, no appreciable effect was noted.

A second QA check was made to determine if any differences existed between the two recorders. The tracking difference between the recorders was checked by electronically generating an input signal to both units simultaneously. A trace from 1 to 100 percent was generated in 5 percent increments. The difference between the two channels was less than one-half of 1 percent.

To assure linearity and a close signal strength between transmissometers, a neutral density filter was used in the reference transmissometer configuration. Prior to conducting any test runs, the transmissometer zero and span values were checked and a three point linearity test conducted using NBS traceable neutral density filters. These tests also were repeated at the end of each run. The calibration results (neutral density filter tests) were used to correct the actual test results to reduce further bias. The bias for each calibration filter was measured by taking 12 readings of each filter. This was a minor correction since all transmissometer systems met EPA Reference Method 9 linearity requirements (3% opacity).

The transmissometer system components used during the smoke generator tests are summarized below

Transmissometer 1 (T1)

- Valtec Selenium cell #R75EB
- Kodak 102 photopic filter
- Tungsten source (2700 K)

Transmissometer 2 (T2)

- Valtec Selenium cell #R75EB
- Kodak 102 photopic filter
- Tungsten source (3100 K), GE EPT 2900
- Corning Glass Works 5900 Daylight Filter
- Neutral Density Filter

Transmissometer 3 (T3)

- Valtec Selenium cell #R75EB
- Tungsten source (2700 K)

SECTION 5

DISCUSSION OF RESULTS

5.1 LABORATORY EVALUATION

Table 1 summarizes the test results from the 14 different transmissometer system tests conducted with the No. 58 and No. 878 filters. Runs 1 through 3 were for the tungsten-photopic system (3 different tungsten sources); Run 4 was the reference system. Runs 6 through 9 were for the near-photopic photocell tungsten source system. In addition to these basic runs, several other system combinations were conducted. Run 5 combined the daylight source with a near-photopic cell, Run 10 combined the 3100 K light source (unfiltered) with a photopic detector, and Run 8 combined the 2700 K tungsten source with the near-photopic detector with the Kodak daylight filter in place. Runs 11 through 14 were conducted using two different photocells--one was a selenium cell from an old smoke generator and the other was a silicon cell with a photopic correction filter as provided by the manufacturer.

Examination of Table 1 indicates that different responses were obtained from the three basic systems tested. The reference system (Run 4) yielded transmittances of 25 and 46 percent for Filters No. 58 and No. 878, respectively. The tungsten-photopic system (Runs 1-3) yielded transmittances of 21 and 42 percent, whereas the tungsten-near-photopic system (Runs 6-9) yielded transmittances of 15 and 33 percent, respectively.

Although a change in system response is noted when the source was changed from daylight to unfiltered tungsten (3% transmittance in the peak response), the major impact on the system response appears to be related to the photopic/near-photopic property of the photocell (9 to 13% transmittance in the peak response). This becomes evident when comparing the results of Runs 4 and 5. In Run 5, the daylight source was used with the near-photopic detector and the transmittance results (14%) compare with those obtained in the near-photopic-tungsten system (15%), but are significantly different than the results obtained in Run 4 with the daylight-photopic system (25%).

TABLE 1. RESULTS OF TEST SYSTEMS

Run number	System		Percent transmittance, %	
	Cell	Light source	Kodak No. 58	ETA No. 878
4	Photopic	Daylight: filtered tungsten source (5900 K)	25	46
1	Photopic	Unfiltered tungsten (2700 K) #93 bulb	21	
2	Photopic	Unfiltered tungsten (2700 K) #1141 bulb	21	42
3	Photopic	Unfiltered tungsten (2700 K) #1073 bulb	21	43
10	Photopic	Unfiltered tungsten (2900 K) #3100 bulb	21	44
5	Near-photopic	Daylight: filtered tungsten source	14	34
6	Near-photopic	Unfiltered tungsten (2700 K) #93 bulb	15	33
7	Near-photopic	Unfiltered tungsten (2700 K) #1141 bulb	15	33
9	Near-photopic	Unfiltered tungsten (2700 K) #1073 bulb	15	33
8	Near-photopic	Tungsten (2700 K)[a] #1073 bulb	15	33
11	Near-photopic[b]	Unfiltered tungsten (2700 K)	15	34
13	Near-photopic[b]	Unfiltered tungsten (2700 K)	17	35
12	Photopic[c]	Unfiltered tungsten (2700 K)	21	44
14	Photopic[d]	Unfiltered tungsten (2700 K)	23	44

[a]With daylight filter.

[b]Selenium cell (International Rectifier, Inc. 1RA15M) from old smoke generator.

[c]Selenium cell (International Rectifier, Inc.) from old smoke generator with Kodak 102 filter added.

[d]Silicon cell with photopic filter as provided from manufacturer (International Rectifier Inc., Green Blaze).

The results of Runs 1-3, 10, 12, and 14, where different unfiltered tungsten sources were used with photopic detectors, indicate that the effect of the different sources is negligible.

The transmittance reduction for the near-photopic systems was significantly different than the transmittance reduction for the photopic systems. Based on these test results we concluded that the simple procedure of using a peak response transmission filter can be used to evaluate whether a transmissometer system is photopic.

To complete the laboratory experiments, the response characteristics of the different transmissometer systems were evaluated using four of the five sharp cutoff filters used in the EMSL study (Kodak No. 4, 21, 29, and 88A). These tests were conducted to compare this technique of evaluating photopic response to the peak-response filter techniques. The results of these tests are summarized in Table 2. Figure 13 presents the measured values plotted on the graphic presentation of the EMSL study results. The results obtained generally fell within the values measured during the EMSL study. The results from the photopic system were closer to the "true photopic" values than the results from the near-photopic system. However, the results were not as clear-cut as with the narrow band filters. From these results we concluded that the peak-response filter test is a better indicator test for photopic response.

5.2 SMOKE GENERATOR EVALUATION

Table 3 summarizes the results of the field test comparing the reference transmissometer system to the partial photopic transmissometer system for both black and white plumes. These data are presented graphically in Figure 14. Table 4 summarizes the results comparing the reference transmissometer system to the near-photopic transmissometer system for both black and white plumes. These data are presented graphically in Figure 15.

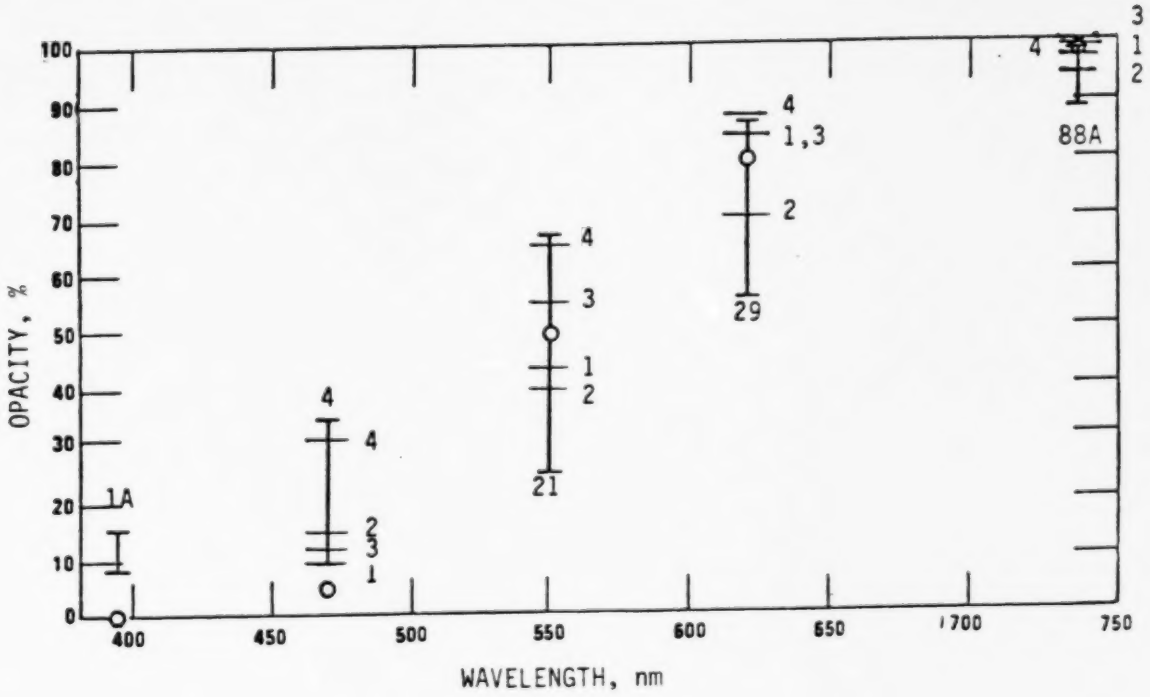
In both cases, the transmissometers correlated better on black smoke than on white smoke. In all cases, the differences between the tested configurations of transmissometers were 5 percent opacity or less. The mean difference and standard deviation of the mean difference were calculated for these data. For the photopic system, the mean difference from the reference system response and the standard deviation of the mean difference were respectively, -1.1 and 1.3

TABLE 2. MULTIPLE CUTOFF FILTER PHOTOPIC TEST

Run	Cell	Source	Percent opacity, %			
			Filter number[a]			
			4	21	29	88A
1	Photopic	Tungsten (2700 K) #1141 bulb	9	43	85	97
2	Near-photopic	Tungsten (2700 K) #1141 bulb	15	40	70	94
3	Photopic	Daylight	12	55	85	100
4	Near-photopic	Daylight	30	65	89	99

[a]"True photopic" filter opacity values:

No. 4 - 5 percent
No. 21 - 50 percent
No. 29 - 81 percent
No. 88A - 100 percent



o Expected response of Photopic System

Range of observed responses, EMSL Study[2]

"1,2,3,4" - Measured response for runs 1, 2, 3, and 4 for Filter Numbers 4, 21, 29, and 88A.

Figure 13. Comparison of cutoff filter results with EMSL study results.

TABLE 3. SUMMARY OF SMOKE GENERATOR TEST RESULTS
REFERENCE PHOTOPIC (I) VS. TUNGSTEN LAMP PHOTOPIC
PHOTOCELL (T_2) TRANSMISSOMETER

Reading number	Measured opacity, %					
	Black smoke			White smoke		
	Reference trans.	Photopic trans.[a]		Reference trans.	Photopic trans.[a]	
		Uncorrected[a]	Corrected[b]		Uncorrected[a]	Corrected[b]
1	0.5	1.0	1.5	0.5	0.5	1.0
2	4.5	6.5	7.0	4.5	4.5	5.0
3	10.0	10.5	11.0	10.0	8.0	8.5
4	14.5	15.5	16.0	15.5	11.5	12.0
5	19.5	20.0	20.5	20.5	18.0	18.5
6	24.5	24.5	25.0	25.0	21.5	22.0
7	30.5	29.0	30.0	30.5	27.0	28.0
8	36.0	34.0	35.0	36.5	31.0	32.0
9	41.0	38.0	39.0	41.0	36.5	37.5
10	47.0	43.5	44.5	45.5	40.0	41.0
11	50.0	48.0	49.0	49.0	43.5	44.5
12	56.0	54.5	56.0	54.0	49.0	50.5
13	60.0	58.0	59.5	61.0	54.5	56.0
14	70.0	67.5	69.0	72.0	64.5	66.0
15	81.5	78.0	79.0	79.5	73.5	74.5
16	92.0	89.0	90.0	91.0	87.0	88.0
17	95.5	94.0	95.0	99.0	97.5	98.5

[a]Actual measured value.

[b]Value corrected for calibration bias as measured by neutral density filters.

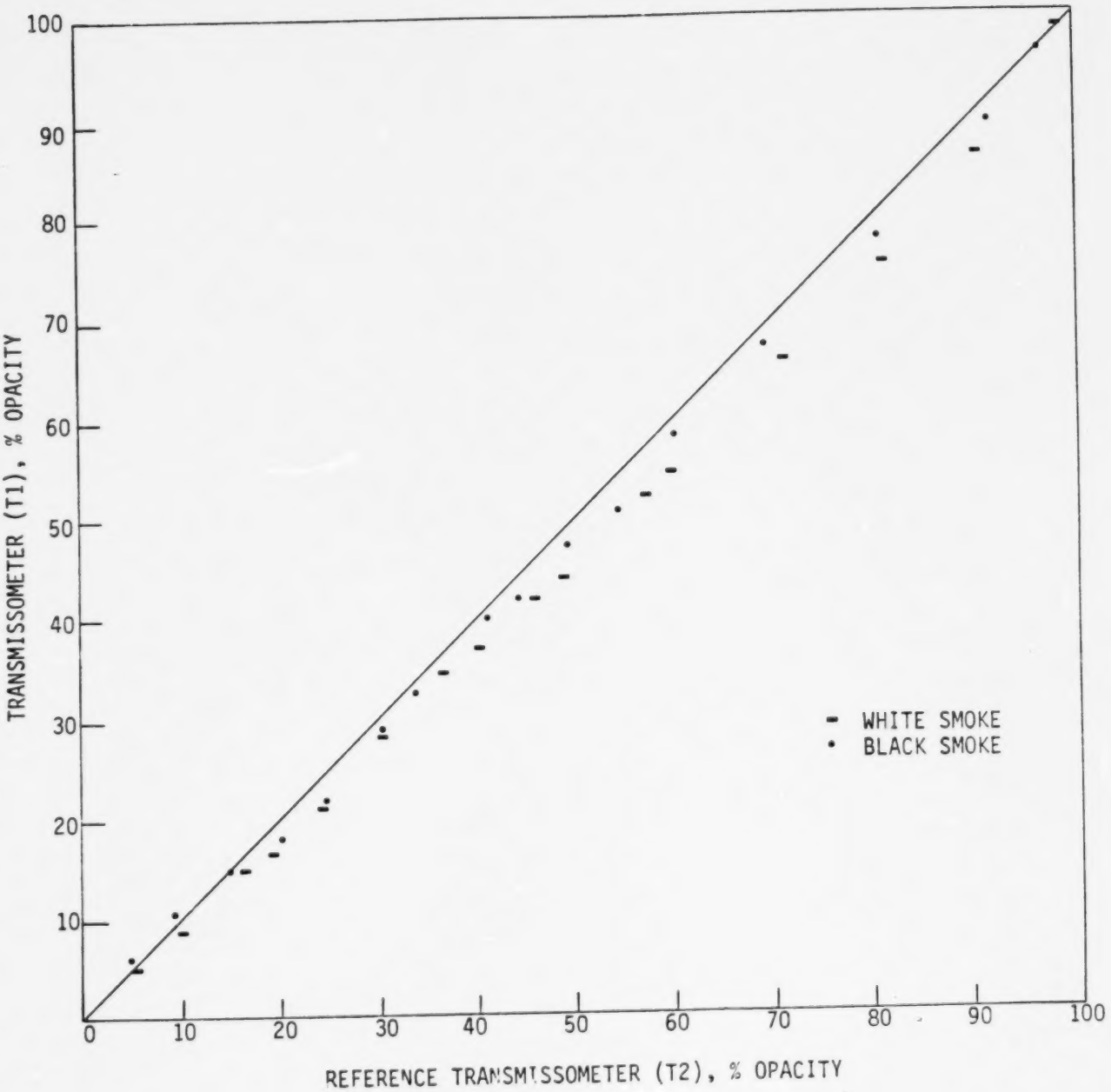


Figure 14. Tungsten lamp photopic photocell transmissometer (T1) response compared to the reference transmissometer (T2).

TABLE 4. SUMMARY OF SMOKE GENERATOR TEST RESULTS
REFERENCE VS. TUNGSTEN LAMP NEAR-PHOTOPIC PHOTOCELL TRANSMISSOMETER

Reading number	Measured opacity, %					
	Black smoke			White smoke		
	Reference trans.	Photopic trans.[a]		Reference trans.	Photopic trans.[a]	
		Uncorrected[a]	Corrected[b]		Uncorrected[a]	Corrected[b]
1	0.5	0.5	1.0	0.0	1.0	1.5
2	5.0	5.5	6.0	5.5	4.5	5.0
3	9.5	10.5	11.0	10.0	8.5	9.0
4	15.0	14.5	15.0	16.5	14.5	15.0
5	20.5	17.0	18.0	19.0	16.0	16.5
6	24.5	21.0	21.5	24.0	20.5	21.0
7	30.5	26.5	28.5	30.5	26.5	28.5
8	33.5	30.5	32.5	36.5	32.5	34.5
9	41.0	38.0	40.0	40.0	35.0	37.0
10	44.0	39.5	41.5	46.0	40.0	42.0
11	49.0	45.0	47.0	49.0	42.0	44.0
12	54.5	50.5	53.0	57.0	50.0	52.5
13	60.0	55.5	58.0	59.5	52.0	54.5
14	69.0	64.5	67.0	71.0	63.0	65.5
15	80.5	76.5	78.0	81.0	74.0	75.5
16	91.5	88.0	89.5	90.5	85.0	86.5
17	96.5	95.0	96.5	98.5	97.5	99.0

[a]Actual measured value.

[b]Value corrected for calibration bias as measured by neutral density filters.

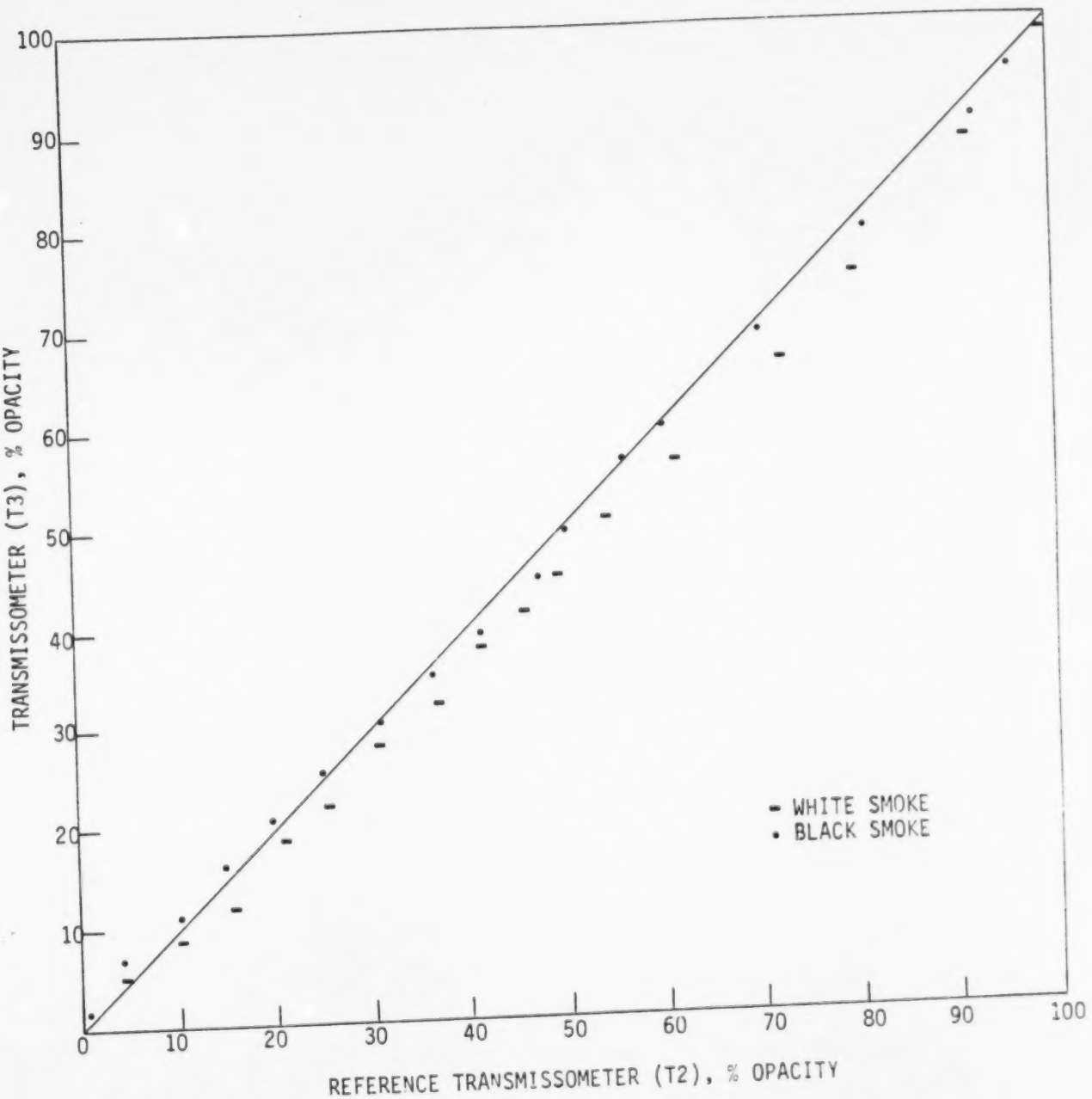


Figure 15. Tungsten lamp near-photopic photocell transmissometer (T3) response compared to the reference transmissometer (T2).

percent opacity for black smoke, and -2.6 and 2.0 percent opacity for white smoke. For the near-photopic system, the mean difference and the standard deviation were -1.1 and 1.3 percent opacity for black smoke, and -2.8 and 2.1 percent opacity for white smoke, respectively.

REFERENCES

1. Condon, E. U., and H. Odishaw. Handbook of Physics. McGraw-Hill Co., New York, New York, 1958. Table 3-1, pp. 6-52.

2. U.S. Environmental Protection Agency. Survey of Transmissometers Used in Conducting Visible Emissions Training Courses, Environmental Monitoring Systems Laboratory. EPA-600/4-78-023, May 1978.

3. Kodak Filters for Scientific and Technical Uses. Standard Book # 0-87985-029-9, Eastman Kodak Company, 1970.

APPENDIX A

PROCEDURES FOR CONDUCTING PHOTOPIC AUDIT TESTS

INTRODUCTION

The purpose of this appendix is to provide the information necessary for testing the transmissometer of a smoke generator in accordance to the spectral response requirements of paragraph 3.3.2.2 of EPA Reference Method 9. This requirement is listed as item (b) of Table 9-1 as published in the method. Specifically, the photocell of the transmissometer is required to have a photopic response. According to paragraph 3.3.2.2, this means that, "...the spectral sensitivity of the cell shall closely approximate the standard spectral-luminosity curve for photopic vision..."

Paragraph 3.3 of Reference Method 9 requires a demonstration at the time of installation to ensure that the smoke meter meets the specifications listed in Table 9-1 of the method. This demonstration shall be repeated following any subsequent repair or replacement of the photocell or associated electronic circuitry including the chart recorder or output meter, or every 6 months, whichever occurs first. The photopic response of the transmissometer therefore needs to be verified at a minimum of every 6 months.

Although these requirements for demonstrating photopic response have existed since publication of Reference Method 9, an acceptable standardized procedure has not existed to conduct this demonstration in the field. The consulting firm of Eastern Technical Associates in Raleigh, North Carolina, researched, developed, and demonstrated the procedure presented in this appendix and has subsequently tested its reliability under field conditions.

The basic concept of photopic response is a major factor in the design of the smoke generator transmissometer. The transmissometer manufacturer selects and uses available components that most closely parallel the standard spectral-luminosity curve for photopic vision. When an adequate parallel response cannot be obtained directly from the best available combination of light source and photocell, selective filtration must be employed. Such filtration should be

kept to a minimum to preclude incorporating components that provide additional possibilities for equipment failure or malfunction. Smoke generators manufactured by Environmental Industries during the past two years have met these requirements and design parameters. Earlier models, models produced by other manufacturers, and units modified in the field are subject to question regarding their capability for photopic response. Therefore a definite need exists for a reliable, reproducible field testing procedure to determine photopic response.

By following the step-by-step procedures outlined in this appendix, any visible emissions trainer can evaluate a transmissometer for photopic response. It is important that each step of the procedures be satisfactorily completed before proceeding to the next step due to the accumulative nature of any errors introduced or allowed. Deviation from the prescribed procedures or experimentation in the field by inexperienced personnel could result in erroneous findings at the conclusion of the test. For example, the use of masking tape or other media instead of the bulldog clip to hold the filters in place can result in filters contaminated with adhesive and/or particulate matter, which may result in incorrect readings.

The presented procedures require that certain conditions be met prior to testing. The transmissometer under examination must have as a minimum, a dependable light source, a stable photocell, and a readout mechanism that indicates directly the percent opacity. Figure A-1 provides a list of equipment required to properly conduct the following steps of the photopic response demonstration. Procedures for electronic calibration, mechanical calibration, linearity check, infrared (IR) response test, near-photopic test, and data analysis are presented in the following subsections. These subsections discuss in detail individual components of the photopic response demonstration. Before conducting this procedure, Reference Method 9 should be reviewed for an overall refresher.

LIST OF REQUIRED EQUIPMENT

Complete smoke generator transmissometer including an appropriate readout mechanism that indicates directly the percent opacity.

Calibration wand of appropriate capacity and a graduated set of interchangeable filter insert plates.

Set of three neutral density filters for determining linearity.

Visible light cutoff filter.

Green photopic test filter.

Span plug for completely obscuring the opening in the filter insert plate.

Bulldog clip or other mechanism for holding filters in place on filter insert plate.

Test data chart for recording results of each test.

Figure A-1. Required equipment list.

PROCEDURES

STEP #1 ELECTRONIC CALIBRATION

1. Allow 30 min warm-up time for the transmissometer and readout device before starting calibration sequence.

2. Ensure that the light source input voltage is within the ±5 percent nominal rated voltage of the light bulb. This voltage cannot be varied for span purposes.

3. Turn light source to OFF position and establish 100 percent electrical span reference point on readout device.

4. Turn light source to ON position and establish electrical zero span reference point on readout device.

5. Repeat steps 2 and 3 until the 0 and 100 percent span points are established without adjustment for 5 consecutive tests, recording data on a photopic response test chart similar to the chart illustrated in Figure A-2.

STEP #2 MECHANICAL CALIBRATION

Smoke generators manufactured prior to 1975 will have varying smoke slot widths. In order to properly conduct the following series of tests, the proper filter insert must be selected to insure that the various test filters are properly positioned in the transmissometer light beam.

Due to the critical nature of the photocell alignment, no part of the transmissometer system should be removed from the stack assembly during calibration or photopic testing. A few degrees of misalignment can shift readings as much as 5 to 10 percent. Inserting the test filters into the center of the stack at the transmissometer crossarm eliminates any need for removing either the light source or photocell assembly.

1. Select the largest insert and assemble it on the wand with no filter in place as illustrated in Figure A-3.

TEST	% OPACITY RESPONSE					
ELECTRICAL ZERO						
ELECTRICAL SPAN						
DYNAMIC ZERO						
DYNAMIC SPAN						
LINEARITY FILTER						
LINEARITY FILTER						
LINEARITY FILTER						
IR FILTER						
NEAR-PHOTOPIC						
TEST NO.	1	2	3	4	5	

GENERATOR OWNER _____ SERIAL # _____

GENERATOR MODEL # _____ MANUFACTURER _____

DATE _____ LOCATION _____ OPERATOR _____

Figure A-2. Example of photopic response test chart.

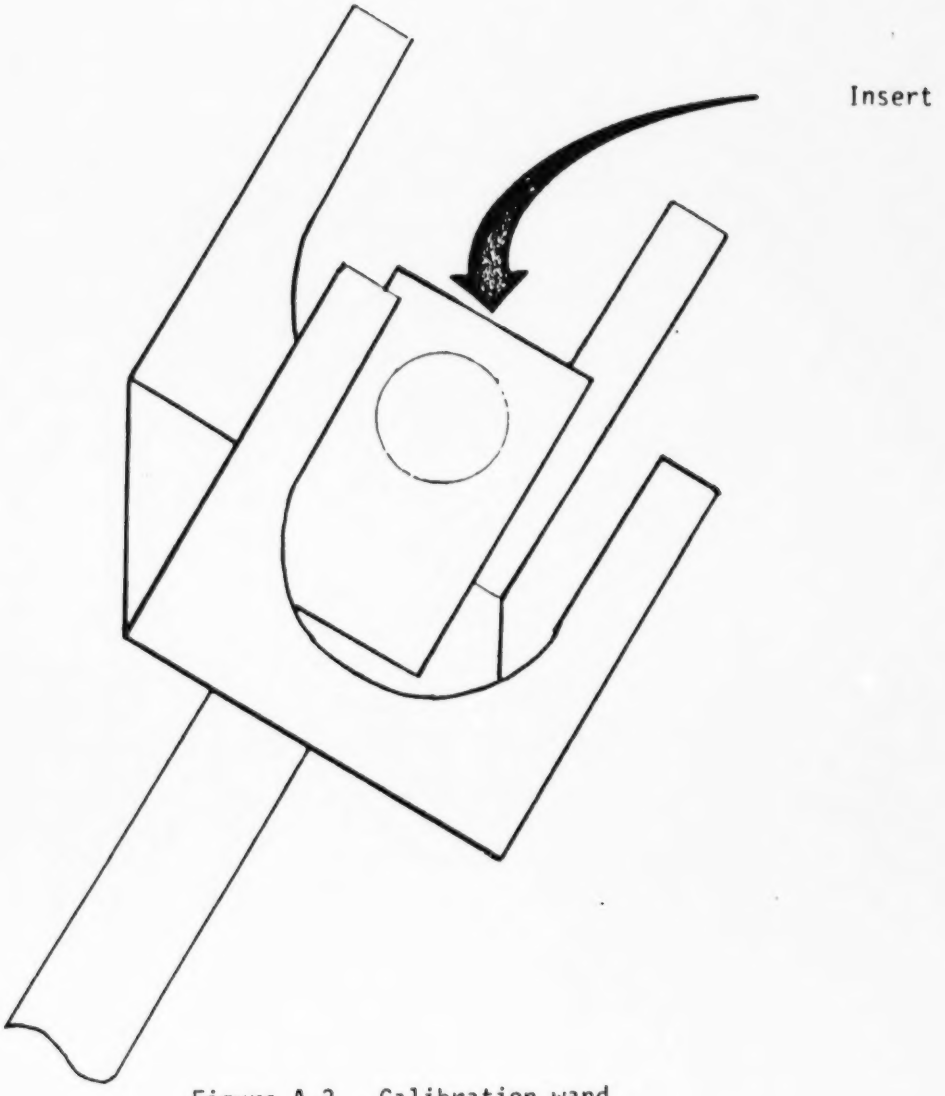


Figure A-3. Calibration wand.

2. With the light source in the ON position, insert the wand in the smoke generator stack to engage the transmissometer as illustrated in Figure A-4.

3. If the assembly slides in place and seats so that the readout system detects its insertion but returns to zero, this insert can be used. Therefore, proceed to Step 4. If the previous requirements are not met, select the next smaller insert and repeat the test. Continue until an insert is selected that will fit and give the response desired.

4. Once the correct insert has been selected and installed on the wand, repeat the seating process four times. With the wand inserted and seated, record the values in percent opacity as the dynamic zero. This assembly of calibration wand with appropriate filter insert attached will be used throughout the remainder of the test procedures.

5. Block the hole in the insert with the span plug, holding it in place with a bulldog clip as illustrated in Figure A-5.

6. Make five insertions of the wand with the span plug installed. Record these values in percent opacity as dynamic span. If the span value is below 97 percent, light is leaking into the system and must be corrected prior to conducting the remaining tests.

STEP #3 LINEARITY CHECKS

1. With the light source in the ON position, insert each of the three neutral density filters into the transmissometer light beam using the selected insert on the calibration wand. Filters are attached to the insert with a bulldog clip. Record the response for each filter on a test chart form similar to the one illustrated in Figure A-2.

2. Repeat step 1 four times for each filter in a random order for a collective total of 15 readings. If any reading exceeds ± 3 percent from the stated filter value, corrective action must be taken prior to subsequent tests.

STEP #4 INFRARED (IR)-RESPONSE TEST

1. Attach the visible cut-off filter to the calibration wand insert with a bulldog clip (Figure A-5).

2. With the light source in the ON position, insert the filter checking that the calibration wand seats fully. Record the percent opacity on the form.

3. Repeat this test four times.

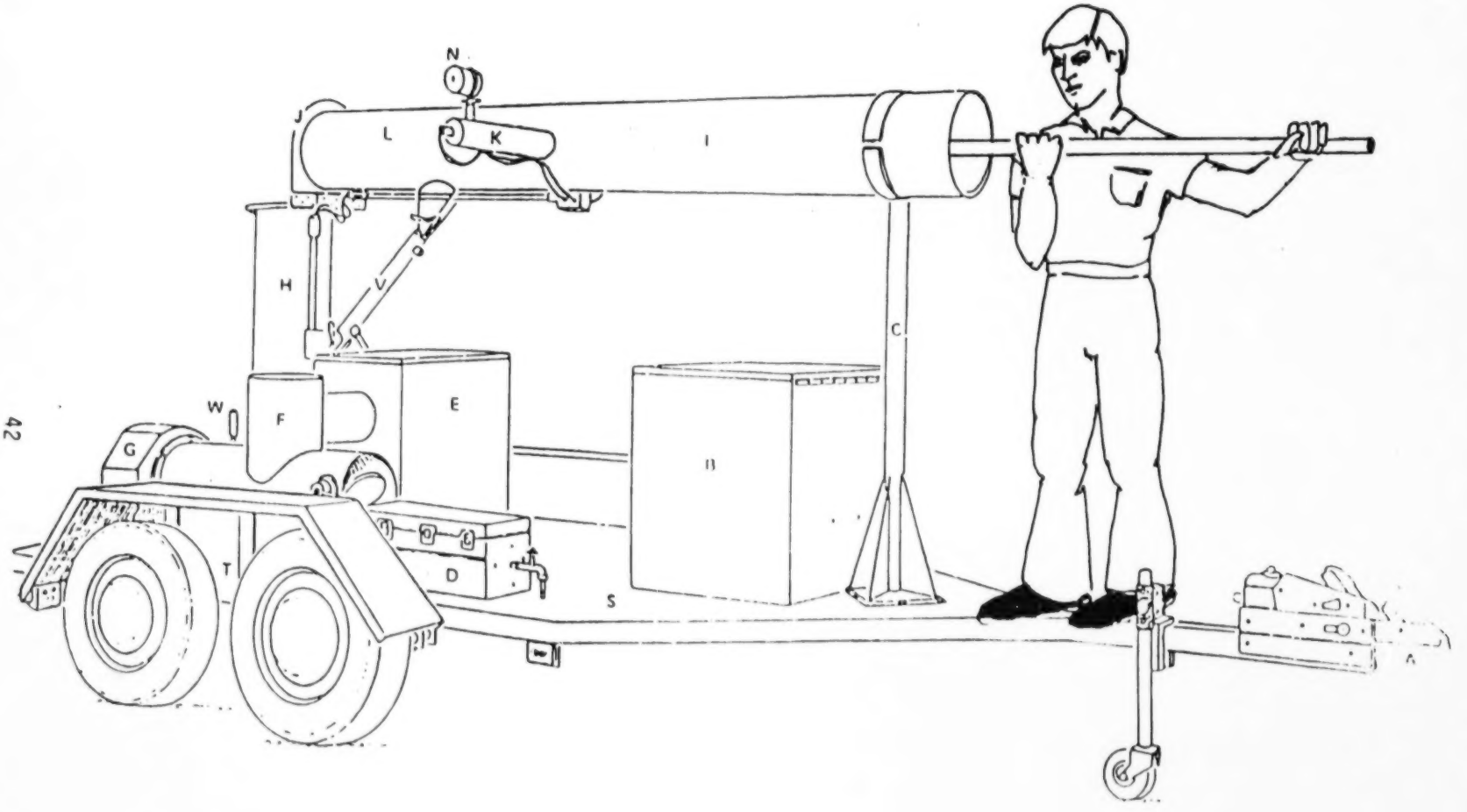


Figure A-4. Illustration of insertion of wand in smoke generator.

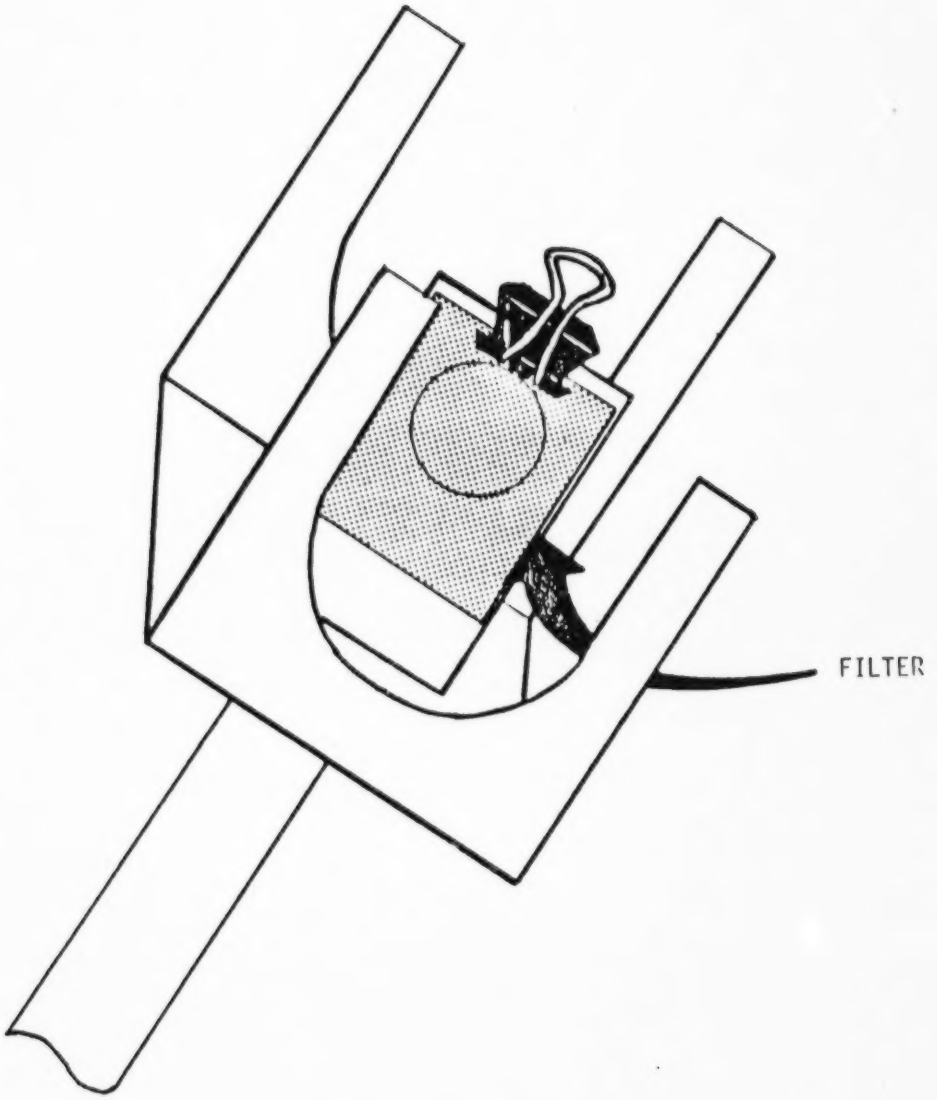


Figure A-5. Calibration wand with span plug.

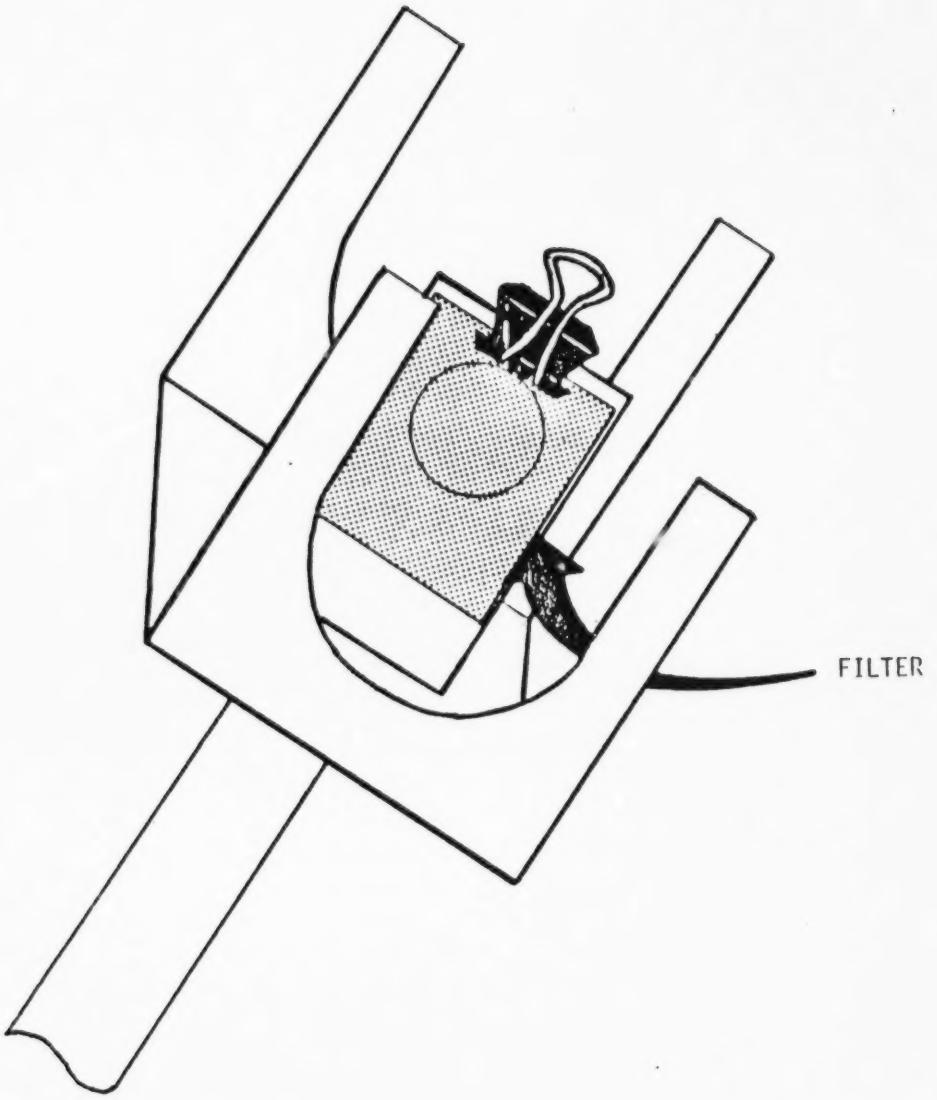


Figure A-5. Calibration wand with span plug.

STEP #5 NEAR-PHOTOPIC TEST

1. Attach the green photopic test filter to the calibration wand insert with a bulldog clip (Figure A-5).

2. With the light source in the ON position, insert the filter and check that the calibration wand is seated fully. Record the percent opacity on the form.

3. Repeat this test four times.

STEP #6 DATA ANALYSIS

1. Sum the five percent opacity responses of the IR filter.

2. Determine the average percent response by dividing the sum by five. Any value less than 97 percent will bias smoke observers-in-training.

3. Sum the five percent-opacity responses of the near-photopic filter.

4. Determine the average percent response by dividing the sum by five. Any value less than 62 percent opacity shows satisfactory near photopic response. Values above 62 percent opacity indicate that an unsatisfactory photopic response has been obtained and that corrective action to the photocell or light source may be needed.

Reference Method

METHOD 9--VISUAL DETERMINATION OF THE OPACITY OF EMISSIONS FROM STATIONARY SOURCES

Reproduced from Appendix A, "Reference Methods," Federal Register, Vol. 39, No. 219; Tuesday, November 12, 1974

Variables Accuracy-

Many stationary sources discharge visible emissions into the atmosphere. these emissions are usually in the shape of a plume. This method involves the determination of plume opacity by qualified observers. The method includes procedures for the training and certification of observers, and procedures to be used in the field for determination of plume opacity. The appearance of a plume as viewed by an observer depends upon a number of variables, some of which may be controllable and some of which may not be controllable in the field. Variables which can be controlled to an extent to which they no longer exert a significant influence upon plume appearance include: Angle of the observer with respect to the plume; angle of the observer with respect to the sun; point of observation of attached and detached steam plume, and angle of the observer with respect to a plume emitted from a rectangular stack with a large length to width ratio. The method includes specific criteria applicable to these variables.

Other variables which may not be controllable in the field are luminescence and color contrast between the plume and the background against which the plume is viewed. These variables exert an influence upon the appearance of a plume as viewed by an observer, and can affect the ability of the observer to accurately assign opacity values to the observed plume. Studies of the theory of plume opacity and field studies have demonstrated that a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background. It follows from this, and is confirmed by field trials, that the opacity of a plume, viewed under conditions where a contrasting background is present can be assigned with the greatest degree of accuracy. However, the potential for a positive error is also the greatest when a plume is viewed under such contrasting conditions. Under conditions presenting a less contrasting background, the apparent opacity of a plume is less and approaches zero as the color and luminescence contrast decrease toward zero. As a result, significant negative bias and negative errors can be made when a plume is viewed under less contrasting conditions. A negative bias decreases rather than increases the possibility that a plant operator will be cited for a violation of opacity standards due to observer error.

Studies have been undertaken to determine the magnitude of positive errors which can be made by qualified observers while reading plumes under contrasting conditions and using the procedures set forth in this method. The results of these studies (field trials) which involve a total of 769 sets of 25 readings each are as follows:

(1) For black plumes (133 sets at a smoke generator), 100 percent of the sets were read with a positive error[1] of less than 7.5 percent opacity; 99 percent were read with a positive error of less than 5 percent opacity.

(2) For white plumes (170 sets at a smoke generator, 168 sets at a coal-fired power plant, 298 sets at a sulfuric acid plant), 99 percent of the sets were read with a positive error of less than 7.5 percent opacity; 95 percent were read with a positive error of less than 5 percent opacity.

The positive observational error associated with an average of twenty-five readings is therefore established. The accuracy of the method must be taken into account when determining possible violations of applicable opacity standards.

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[1]For a set, positive error = average opacity determined by observers 25 observations — average opacity determined from transmissometer s 25 recordings

Principle and Applicability-

1. Principle and applicability.

1.1 Principle. The opacity of emissions from stationary sources is determined visually by a qualified observer.

1.2 Applicability. This method is applicable for the determination of the opacity of emissions from stationary sources pursuant to § 60.11(b) and for qualifying observers for visually determining opacity of emissions.

Procedures for Opacity Observations-

2. Procedures.

The observer qualified in accordance with paragraph 3 of this method shall use the following procedures for visually determining the opacity of emissions.

2.1 Position. The qualified observer shall stand at a distance sufficient to provide a clear view of the emissions with the sun oriented in the 140° sector to his back. Consistent with maintaining the above requirement, the observer shall, as much as possible, make his observations from a position such that his line of vision is approximately perpendicular to the plume direction, and when observing opacity of emissions from rectangular outlets (e.g. roof monitors, open baghouses, noncircular stacks), approximately perpendicular to the longer axis of the outlet. The observer's line of sight should not include more than one plume at a time when multiple stacks are involved, and in any case the observer should make his observations with his line of sight perpendicular to the longer axis of such a set of multiple stacks (e.g. stub-stacks on baghouses).

2.2 Field records. The observer shall record the name of the plant, emission location, type facility, observer's name and affiliation, and the date on a field data sheet (Figure 9-1). The time, estimated distance to the emission location, approximate wind direction, estimated wind speed, description of the sky condition (presence and color of clouds), and plume background are recorded on a field data sheet at the time opacity readings are initiated and completed.

2.3 Observations. Opacity observations shall be made at the point of greatest opacity in that portion of the plume where condensed water vapor is not present. The observer shall not look continuously at the plume, but instead shall observe the plume momentarily at 15-second intervals.

2.3.1. Attached steam plumes. When condensed water vapor is present within the plume as it emerges from the emission outlet, opacity observations shall be made beyond the point in the plume at which condensed water vapor is no longer visible. The observer shall record the approximate distance from the emission outlet to the point in the plume at which the observations are made.

Procedures (cont.)-

2.3.2 Detached steam plume. When water vapor in the plume condenses and becomes visible at a distinct distance from the emission outlet, the opacity of emissions should be evaluated at the emission outlet prior to the condensation of water vapor and the formation of the steam plume.

2.4 Recording observations. Opacity observations shall be recorded to the nearest 5 percent at 15-second intervals on an observational record sheet. (See Figure 9-2 for an example.) A minimum of 24 observations shall be recorded. Each momentary observation recorded shall be deemed to represent the average opacity of emissions for a 15-second period.

2.5 Data Reduction. Opacity shall be determined as an average of 24 consecutive observations recorded at 15-second intervals. Divide the observations recorded on the record sheet into sets of 24 consecutive observations. A set is composed of any 24 consecutive observations. Sets need not be consecutive in time and in no case shall two sets overlap. For each set of 24 observations, calculate the average by summing the opacity of the 24 observations and dividing this sum by 24. If an applicable standard specifies an averaging time requiring more than 24 observations, calculate the average for all observations made during the specified time period. Record the average opacity on a record sheet. (See Figure 9-1 for an example.)

Qualifications and Testing-

3. Qualifications and testing.

3.1 Certification requirements. To receive certification as a qualified observer, a candidate must be tested and demonstrate the ability to assign opacity readings in 5 percent increments to 25 different black plumes and 25 different white plumes, with an error not to exceed 15 percent opacity on any one reading and an average error not to exceed 7.5 percent opacity in each category. Candidates shall be tested according to the procedures described in paragraph 3.2. Smoke generators used pursuant to paragraph 3.2 shall be equipped with a smoke meter which meets the requirements of paragraph 3.3.

The certification shall be valid for a period of 6 months, at which time the qualification procedure must be repeated by any observer in order to retain certification.

Certification Procedure-

3.2 Certification procedure.

The certification test consists of showing the candidate a complete run of 50 plumes—25 black plumes and 25 white plumes—generated by a smoke generator. Plumes within each set of 25 black and 25 white runs shall be presented in random order. The candidate assigns an opacity value to each plume and records his observation on a suitable form. At the completion of each run of 50 readings, the score of the candidate is determined. If a candidate fails to qualify, the complete run of 50 readings must be repeated in any retest. The smoke test may be administered as part of a smoke school or training program, and may be preceded by training or familiarization runs of the smoke generator during which candidates are shown black and white plumes of known opacity.

Smoke Generator Specifications-

3.3 Smoke generator specifications.

Any smoke generator used for the purposes of paragraph 3.2 shall be equipped with a smoke meter installed to measure opacity across the diameter of the smoke generator stack. The smoke meter output shall display instack opacity based upon a path length equal to the stack exit diameter, on a full 0 to 100 percent chart recorder scale. The smoke meter optical design and performance shall meet the specifications shown in Table 9-1. The smoke meter shall be calibrated as prescribed in paragraph 3.3.1 prior to the conduct of each smoke reading test. At the completion of each test, the zero and span drift shall be checked and if the drift exceeds ±1 percent opacity, the conditions shall be corrected prior to conducting any subsequent test runs. The smoke meter shall be demonstrated, at the time of installation, to meet the specifications listed in Table 9-1. This demonstration shall be repeated following any subsequent repair or replacement of the photocell or associated electronic circuitry including the chart recorder or output meter, or every 6 months, whichever occurs first.

Table 9-1. Smoke Meter Design and Performance Specifications

Parameter	*Specification*
a. Light source	*Incandescent lamp operated at nominal rated voltage.*
b. Spectral response of photocell.	*Photopic (daylight spectral response of the human eye—reference 4.3).*
c. Angle of view	*15° maximum total angle.*
d. Angle of projection	*15° maximum total angle.*
e. Calibration error	*±3% opacity, maximum*
f. Zero and span drift.	*±1% opacity, 30 minutes.*
g. Response time	*≤5 seconds.*

Calibration of Smoke Meter-

3.3.1 Calibration. The smoke meter is calibrated after allowing a minimum of 30 minutes warmup by alternately producing simulated opacity of 0 percent and 100 percent. When stable response at 0 percent or 100 percent is noted, the smoke meter is adjusted to produce an output of 0 percent or 100 percent, as appropriate. This calibration shall be repeated until stable 0 percent and 100 percent readings are produced without adjustment. Simulated 0 percent and 100 percent opacity values may be produced by alternately switching the power to the light source on and off while the smoke generator is not producing smoke.

Smoke Meter Evaluation-

3.3.2 Smoke meter evaluation. The smoke meter design and performance are to be evaluated as follows:

3.3.2.1 Light source. Verify from manufacturer's data and from voltage measurements made at the lamp, as installed, that the lamp is operated within ±5 percent of the nominal rated voltage.

3.3.2.2 Spectral response of photocell. Verify from manufacturer's data that the photocell has a photopic response; i.e., the spectral sensitivity of the cell shall closely approximate the standard spectral-luminosity curve for photopic vision which is referenced in (b) of Table 9-1.

3.3.2.3 Angle of view. Check construction geometry to ensure that the total angle of view of the smoke plume, as seen by the photocell, does not exceed 15°. The total angle of view may be calculated from: $\theta = 2 \tan^{-1} d/2L$, where θ = total angle of view, d = the sum of the photocell diameter + the diameter of the limiting aperture, and L = the distance from the photocell to the limiting aperture. The limiting aperture is the point in the path between the photocell and the smoke plume where the angle of view is most restricted. In smoke generator smoke meters this is normally an orifice plate.

3.3.2.4 Angle of projection. Check construction geometry to ensure that the total angle of projection of the lamp on the smoke plume does not exceed 15°. The total angle of projection may be calculated from: $\theta = 2 \tan^{-1} d/2L$, where θ = total angle of projection, d = the sum of the length of the lamp filament + the diameter of the limiting aperture, and L = the distance from the lamp to the limiting aperture.

3.3.2.5 Calibration error. Using neutral-density filters of known opacity, check the error between the actual response and the theoretical linear response of the smoke meter. This check is accomplished by first calibrating the smoke meter according to 3.3.1 and then inserting a series of three neutral-density filters of nominal opacity of 20, 50, and 75 percent in the smoke meter pathlength. Filters calibrated within ±2 percent shall be used. Care should be taken when inserting the filters to prevent stray light from affecting the meter. Make a total of five nonconsecutive readings for each filter. The maximum error on any one reading shall be 3 percent opacity.

3.3.2.6 Zero and span drift. Determine the zero and span drift by calibrating and operating the smoke

generator in a normal manner over a 1-hour period. The drift is measured by checking the zero and span at the end of this period.

3.3.2.7 Response time. Determine the response time by producing the series of five simulated 0 percent and 100 percent opacity values and observing the time required to reach stable response. Opacity values of 0 percent and 100 percent may be simulated by alternately switching the power to the light source off and on while the smoke generator is not operating.